Amplified socio-technical problems in converging infrastructures

A novel topic for technology assessment?

Christian Büscher, *Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT),*
Karlstr. 11, 76133 Karlsruhe (christian.buescher@kit.edu) *https://orcid.org/0000-0002-8793-2438*
Michael Ornetzeder, *Institute of Technology Assessment (ITA), Austrian Academy of Sciences (ÖAW) (michael.ornetzeder@oeaw.ac.at)*
Bert Droste-Franke, *IQIB – Institut für qualifizierende Innovationsforschung & -beratung (bert.droste-franke@iqib.de)*

Converging infrastructures illustrate the complexity of the processes involved in both operational sector coupling and socio-technical sector integration. What consequences of this development can technology impact research estimate today and what difficulties will arise in doing so? This article introduces the TATuP special topic as well as the individual contributions and also addresses socio-political aspects, beyond the usual questions of technical feasibility and efficiency: What strategies are developed to initiate and control comprehensive change? What are the mechanisms to maintain the ability to act despite great uncertainties for all those concerned with future converging infrastructures for energy, transport, and heating/cooling. The interdisciplinary approach to the topic focuses on three central "socio-technical problems" and gives a first insight into the conditions under which converging infrastructures emerge and what consequences these processes might have.

Die Verschärfung sozio-technischer Probleme in konvergierenden Infrastrukturen
Ein neues Thema für die Technikfolgenabschätzung?

Konvergierende Infrastrukturen verdeutlichen die Komplexität in Prozessen der operationalen Sektorkopplung sowie der soziotechnischen Sektorintegration. Welche Konsequenzen dieser Entwicklung kann die Technikfolgenforschung bereits jetzt abschätzen und welche Schwierigkeiten ergeben sich dabei? Dieser Artikel stellt das TATuP-Thema sowie die einzelnen Beiträge vor und stellt neben technischer Machbarkeit und Effizienz auch explorative Fragen nach gesellschaftspolitischen Aspekten: Welche Strategien sollen den umfassenden Wandel initiieren und kontrollieren? Welche Mechanismen erlauben Handlungsfähigkeit trotz großer Unsicherheiten für zukünftige Akteure konvergierender Infrastrukturen für Energie, Transport und Wärme/Kühlung? Der interdisziplinäre Ansatz orientiert sich an drei zentralen „soziotechnischen Problemen" und gibt einen ersten Einblick, unter welchen Bedingungen konvergierende Infrastrukturen entstehen und welche Konsequenzen diese Prozesse möglicherweise haben werden.

Keywords: *sector coupling and integration, energy and transport, complexity and control, change and stability, action under uncertainty*

The convergence of infrastructures: promise or paradigm?

The coupling of infrastructure sectors such as energy and transport or heating and cooling is becoming an important topic in energy transition studies. Sector coupling may not only lead to an overall more efficient use of energy but also make a substantial contribution to the more widespread use of renewable energy sources (RES). Scholars and practitioners approach the topic from very different perspectives and with different goals. There are, for example, publications on scenario-building and meta-studies (Ausfelder et al. 2017), modeling (Robinius et al. 2017a, 2017b), case studies and visions (Canzler and Knie 2013), economic reports (acatech et al. 2018), governance research (Hoffrichter and Beckers 2018), and stakeholder analyses (Bauknecht et al. 2018). However, the question remains whether sector coupling is still in the stage of an *expectation statement*, i. e., the explication of a vision, an emerging technology, or a "promising technology" (van Lente 2000, p. 60), or whether we are actually witnessing the consolidation of a scientific, economic, or political *agenda* (Bender 2005). Proponents of this approach no longer discuss sector coupling only as a promise to

---

https://doi.org/10.14512/tatup.29.2.11

increase resource use efficiency and an opportunity to reduce greenhouse gas emissions, but agree *in unison* that it is an essential *requirement for slowing* down climate change. However, sector coupling goes far beyond the technical coupling of production and consumption systems. The success of technical sector coupling depends on socio-technical sector integration through consideration and combination of multiple types of knowledge, the creation of new social networks, the alignment of technical norms and standards, and new forms of social coordination in markets and in regulation between actors and sectors. For this reason, we propose the term "converging infrastructures", which ultimately implies the interlinking and transformation of existing socio-technical systems. Converging infrastructures illustrate the complexity of the processes involved in both operational sector coupling and socio-technical sector integration.

There is evidence suggesting that integrated approaches will become increasingly important in the coming years, not only in research but also through the implementation of political measures or the realization of infrastructure projects. Against this background, some important questions arise:

- To what extent is it possible to combine previously separate infrastructures into integrated entities in the future?
- What social and technical implications and risks would such far-reaching changes entail?
- Finally, how could the emerging complexity be adequately investigated and how should possible consequences be addressed?

This TATuP special topic aims to provide some preliminary considerations on converging infrastructures and thus provide a stimulus to further explore the possibilities and consequences of this development from the perspective of different disciplines. Therefore, we propose the concept of *socio-technical problems* as a heuristic to gain insights from various disciplinary perspectives. This concept was initially developed to identify common *reference problems* in interdisciplinary energy research.[1] The underlying idea was to support a cognitive integration of various contributions without burdening the collaborative work with excessive discussions on the identification of shared research objects (Büscher et al. 2018).

What are socio-technical problems?

Many scholars in the field of energy transitions emphasize the need to consider technical systems, organizations, regimes or networks, as well as individual and collective action affecting system operations (Geels 2004; Bolton and Foxon 2015; Cherp et al. 2018). Terms such as socio-technical systems, actor networks, or social practices are used to emphasize the close interrelation between technical artifacts or operations, on the one hand, and social behavior, action, or decision making, i. e., communication, on the other. We assume that the topic of sector coupling needs to be addressed in a similar way – in reference to technical *and* social elements.

Furthermore, researchers argue that system transitions are triggered if societal functions are at risk, since unsustainable consumption of fossil fuels endangers energy supply and promotes climate change. Grin et al. (2010, pp. 2) argue that "persistent problems" deeply embedded in the structure of social systems result in innovative practices and structural adaptation, which eventually lead to system innovation and transitions as a possible response to these problems. However, the ever increasing complexity of energy supply observed in recent years produces a growing variety of solutions to existing problems, and these "solutions" almost simultaneously lead to new problems (Schuitmaker 2012, p. 1023). We only have to consider how the introduction and implementation of RES during the last decades has partly replaced fossil energy supply and brought about new challenges for storage and transport (e. g., of electricity), for the organization of production (market interaction, regulation), or for legislative decision making regarding the installation of corresponding infrastructures (power plants, physical networks).

The historian Paul Edwards, who sees large infrastructures not only as solutions to societal problems but also as a constant challenge, argues in the same direction: "The overall [socio-technical] system can be fruitfully described as posing a linked series of socio-technical problems" (Edwards 2004, p. 209). He thus refers to problems that cannot be reduced to either technical or social characteristics, that cannot be solved for good, i. e., definitively, and that need to be addressed constantly, i. e., today, tomorrow, next year, and, if we think about sustainability, for the next centuries.

Existing research from science and technology studies (STS), large technical systems theory (LTS), systems theory, transition and innovation research, etc. offers a rich body of literature that helped to identify core issues and thus to reformulate them as the following socio-technical problems (Büscher et al. 2018):

- The factual dimension refers to the issue of the increasingly complex interaction between technical and social elements, such as physical installations and networks with social organization, and the ensuing quest for maintaining control, e. g., in terms of predictability, security, safety, efficiency, etc. (problem of control).
- The social dimension focuses on generally shared expectations, i. e., institutions, where the different participants involved in the provision and use of services (actors, parties, persons, agents, stakeholders, organizations, etc.) find mutual orientation, and where change is enacted upon or by the activities of all parties involved (problem of change).

---

[1] The concept started to take shape in the Helmholtz Alliance ENERGY-TRANS (2011–2016), which consisted of an interdisciplinary group of about 80 researchers from different disciplinary backgrounds who investigated the interactions between technical and societal developments in the context of the German energy transition (www.energy-trans.de).

- The temporal dimension stresses the need to act in the present, despite the past serving only as experience and the future not yet being known, as well as the problem of coping with uncertainty and risk. This dimension is particularly affected by the consequences of energy transitions, because the resulting structural complexity and institutional change increase non-transparency and challenge the ability to act and take decisions (problem of action).

All three problem dimensions represent, in an abstract way, challenges for the energy complex as a whole as well as for the ongoing energy transition. These dimensions serve as an analytical heuristic; they are simultaneously effective and influence each other, as will be discussed in more detail below.

Control despite complexity

The problem of energy supply is addressed through a heterogeneous structure of a comprehensive energy complex comprising several technical and organizational systems and subsystems. The notion of structure refers to a chain of technical and social events that at best produces the expected output (Hughes 1983, p. 5). System structures aim to enable control of technical operation and social activities as well as the interaction of both, in particular to align the actual behavior of a system with its intended behavior (Nightingale et al. 2003, p. 484). In this sense, technology is always operated within the medium of *instrumentality* and under conditions of limited operating principles (*conservation, transformation, storage,* and *transmission*) (Beckman 1994, p. 320). In complicated technical systems, all of these principles come into effect simultaneously, and thus technology represents the *determination of production* and *demand* (of services and goods).

In the early stages of the development of power grids, control was the major problem if further rationalization and optimization was to be realized (Hughes 1983, p. 367). In order to achieve economically effective operation, operators had to align physical structures and machine operation with increasingly sophisticated means of social organization in order to manipulate the "load factor" (the ratio of actual energy output to the theoretical maximum output of a power plant) of the system. In the search for the most economically effective system architecture, system traffic must be allocated. Capacity utilization changes from moment to moment, as does the internal state, the load factor, which must be continuously optimized. Consequently, social settings are required to safeguard critical functions: the organization of operation monitoring (metering, comparing, compensating, actuating), the coordination of activities; the restriction of access to the system or network; the starting-up or shutting-down of facilities connected to the overall system (Künneke et al. 2010, p. 499).

These challenges, as we assume, have become more acute in recent decades with the introduction and dissemination of RES, energy storage options, and new market models (Droste-Franke et al. 2012). We must assume that the problem of control will intensify with recent developments of sector integration.

Change despite stability

Sustaining functions while simultaneously enabling change refers to the problem of balancing *redundancy* and *variety* (Atlan 1974, p. 300). The transition from one system to another (or the transformation of a system during operation) implies changes while society still depends on the output and services of the system. Structural changes affect the way social actors orient themselves mutually in the complexity of the energy system. Users expect energy services that are reliable, safe, and affordable, and this expectation is deeply entrenched in the industrialized world. The major changes that began in the nineteenth century – the shift from a biomass-based to a fossil fuel-based economy and the diversification of energy sources (Fouquet 2016) – led to industrial society's dependence on the exponential exploitation of energy sources such as coal, oil, or gas (Hagens 2020, p. 5). Since then, energy infrastructures have been operated in a highly *redundant* mode – reliably providing energy through refineries and pipelines as well as large power plants and vast networks. The transformation of energy systems worldwide will change this situation. After decades of successful deployment of conventional means of energy supply, the contingency of such paradigms has been revealed through the increasing use of renewable energy sources, decentralized network architectures, and novel business models (including, for example, small municipal cooperatives).

However, transformations that *vary greatly* in their degree, scope, and pace result in high complexity (Gallagher et al. 2012, p. 144). Stable orientation may get lost and the self-organizing capacities of social systems are at stake (Atlan 1974, p. 300). Both variety and redundancy are essential, but too much variety leads to volatile, erratic behavior, whilst too much redundancy causes *inertia*, *lock-ins*, and *path dependencies* (which in turn maintain redundancy).

In our case, it is interesting to look into the possible drivers (derived from research on energy transitions) of sector integration. These may be technical and social innovations that challenge established regimes (Geels 2014); energy and climate policy initiatives that aim to transform existing systems (Cherp et al. 2018); synchronized development processes designed to involve actors at all relevant levels, e. g., in the area of knowledge acquisition and exchange; processes of behavioral change as part of innovation processes, i. e., "exnovation" of established practices and commonly shared knowledge (David and Gross 2019); changes and events in the external landscape that also put pressure on the regimes (e. g., technical accidents and effects of climate change, as well as global recessions and pandemics).

Action(ability) despite non-transparency

In converging infrastructures we will encounter many physical, digital, and social relationships between systems (e. g., power plants, vehicles, manufacturing facilities), networks of systems (e. g., smart grids), and networks of networks (e. g., Internet of Everything), as well as between diverse social actors such as operators and designers, legislators, controllers, electricity suppliers, and customers and many more. In these socio-technical constellations, many of the emerging relationships take the form of "flat" screens for the user interface, as opposed to the "deep" and complicated structure of the system behind the surface. This increases the experience of non-transparency of relevant operations and thus of uncertainty and risk (Büscher 2018, p. 26 ff.).

Within socio-technical constellations, operators are responsible for maintaining control from moment to moment, taking account of planned changes toward the convergence of infrastructures. The modeling of possible failures and threats in order to address vulnerabilities or increase resilience is a serious challenge (Kröger and Nan 2018). Lack of data hampers informed decision making. Uncertainty must be absorbed by distributing risks and responsibilities, legal protection, and informal mechanisms such as trust and confidence. In situations of change, plausible decision-making programs replace accurate calculations for decision making (Weick et al. 2005, p. 415). In practice, the problem of coping with uncertainty exists, for example, with respect to interconnected infrastructures (Roe and Schulman 2016, p. 62). In order to ensure reliable operation even beyond the planned and intended design, engineers, policy makers, or managers, must trust in the skills and knowledge of the practitioners operating the facilities from moment to moment (Roe and Schulman 2016, p. 156).

In addition, visions of smart grids and novel markets propose a bi-directional data exchange between providers and consumers. Especially consumers are expected to be involved more actively in both the production and consumption of electricity. The term prosumer clearly indicates these changes on the supply side. The industry is searching for viable business cases and models for smart appliances and prosumer roles, as already seen in "virtual power plants" (Dürr and Heyne 2017), while politicians, administrators, and consumer protection associations are looking for ways to enable innovation and protection of prosumers at the same time (Covrig et al. 2014, p. 87). Moreover, the problem of lack of insight into the behavior, e. g., the algorithms, of smart technology may progressively become the most important issue for all parties involved (Milchram et al. 2018, p. 11).

Contributions

It is well recognized that sector integration is of considerable importance to the transition of the energy system toward decarbonization goals. And it is very likely that its importance will increase in the coming years. However, the benefits of this approach face a number of critical challenges. The underlying rationale for this TATuP special topic is the legitimate assumption that converging infrastructures, i. e., the operational coupling and social, organizational, and institutional integration of sectors, *will significantly increase socio-technical problems*, as briefly sketched above. Socio-technical entities, which incorporate a large number of heterogeneous elements and interrelationships, already today impose a high degree of complexity on operators, supervisors, and users and will most likely become even more complex in the future. As a result, the effort required for controlling and governing these systems – both their operation and transition – will increase significantly. New risks and side effects will certainly arise that are difficult to predict. One way to deal with this situation is to address the resulting socio-technical problems in their factual, social, and temporal dimension. The contributions to this special topic refer to these dimensions and the associated dilemmas in a number of ways. In this sense, the contributions in this volume further explore, test, and deepen the concept of converging infrastructures from various disciplinary perspectives:

In their contribution, Christian Büscher, Dirk Scheer, and Lisa Nabitz take up the challenge of reviewing existing knowledge about sector coupling and its various implications. They do so by drawing on the concept of socio-technical problems, which should make it possible to better portray the manifold consequences and risks of integrating several sectors and forms of energy. They note that sector coupling is widely seen as a promising strategy to increase resource and energy efficiency and, thus, to reduce greenhouse gas emissions, but that it is typically accompanied by greater technical and social diversity. This increases, among other things, the complexity of existing systems, entails uncertainties and risks, and increases the need for coordination between various actors. A number of studies claim that politics has a central role to play as initiator and facilitator of the intended infrastructural changes. Although the associated political risks are known, there is a lack of analyses of possible strategies to deal with such risks. The review also shows, however, that there are hardly any studies that deal with the risks and uncertainties associated with the operation of integrated infrastructures. The authors conclude that future research should address issues such as exnovation, the coordination of key innovation actors, or the role of multi-level governance systems in more detail to better reflect the socio-technical nature of converging infrastructures.

Oberle at al. present an analysis of options for residential heating, which shows the relevance of sector coupling and the need for active coordination of the transformation processes in this area. They start with the characterization of the three competing infrastructures gas networks, heating networks, and electricity grids as well as the respective options for installed heating devices. Based on current conditions and a projection for 2050, an aggregated assessment of all costs and CO_2 emissions of the currently most relevant and promising variants of gas condensing boilers, heat pumps, and connections to a heating network is carried out. With natural gas and synthetic methane, two options for gaseous fuels are considered. The resulting cost estimates show large differences and reveal that sector coupling needs to be taken into account in future infrastructure planning. In designing infrastructures during the transformation process, such analyses need to be considered, but be complemented by more in-depth research and against the background of socio-technical systems with wider consideration of disciplinary aspects, options, impacts, and framework conditions.

The case of the Dutch energy transition strengthens the argument of continuous socio-technical problems. In order to achieve the ambitious decarbonization policy objectives, as Romi Dekker and Rinie van Est claim, Dutch policy focuses primarily on technical solutions, i. e., renewable energy sources. The dissemination of RES brings about many new problems. In this case, the need for "smarter" control of a decentralized, distributed energy complex in conjunction with electrified transport and heating. The core believe of Dutch policy is "digitalization" (besides liberalization and privatization), because only information and communication technology promises to help secure reliable, efficient, affordable, and inclusive services. Dekker and van Est emphasize in this context that digitalization is becoming an integral part of any political agenda in response to increasing complexity (from promise to requirement). However, it is precisely the means of mitigating the problem of complexity that contributes to this situation: "On the other hand, since they increase the diversity of actors and add new roles, smart grids also add extra complexity with regard to organizing the electricity market" (Dekker and van Est in this issue, p. 34). In the future, topics such as digital security, data governance, equality, and justice in the distribution of costs and benefits as well as a (presumably government-led and observed by non-governmental actors) supervision of digitalization will become pressing issues for academic research (especially TA), policy making, and public debate.

Michael Ornetzeder and Tanja Sinozic present an example of a pilot project in which several novel technologies are tested in an actively designed niche situation. The case study is about a smart energy housing project in Austria, in which the heating, gas, and electricity sectors were interlinked in several ways. They show that sector coupling in this case was substantially supported by niche protection activities, which enabled the development of a comprehensive actor network structure, and by long-established cognitive and organizational routines. Among other things, it seemed to be crucial for the implementation of the pilot project that the main project owner had a long history as a multi-utility company and that services and infrastructure units were never completely unbundled in the course of the liberalization of the energy markets. This constellation enabled an effective management of potential technical, economic, and organizational risks. The example also shows that end users are not entirely satisfied with the monopoly-like situation resulting from the arrangement applied. Furthermore, the project setting and the design of the follow-up projects implemented under current market conditions show that the economic and legal framework conditions still need to change in order to realize the full potential of sector coupling.

Finally, Bert Droste-Franke presents the manifold perils and challenges for the theory and practice of systems analysis in the case of converging infrastructures. Droste-Franke emphasizes that the basic socio-technical problems outlined above also apply to systems analysis and corresponding scientific modeling efforts. The approach becomes self-reflexive. Looking at the science-policy interface, Droste-Franke raises questions about the quality of models and the underlying presumptions and premises in relation to, *first*, the research object of interest, i. e., the complex of operating and simultaneously transforming systems, and, *second*, in relation to the need for system knowledge. The latter refers to the attempt to clarify the conditions for providing sound advice that is instructive for different actors in different situations. For the topic of converging infrastructures, the problem of controlling all relevant elements and their interrelations in the modeling process becomes prevalent. Predicting the innovation dynamics resulting from a myriad of micro processes compared to past developments also becomes a challenge. Consequently, also modeling methods must be altered to take account of multiple disciplinary insights and expose constant patterns in innovation dynamics (redundancy in a stream of varying events). Coping with uncertainty in modeling is therefore an inherent feature of this work. Also, finding the means to communicate scientific uncertainty to those seeking advice is crucial. The mode of communication seems decisive to foster some confidence in scientific expertise. Only then can decision makers on the future course of sector integration be put in a position to act based on the information provided.

References

acatech et al. – National Academy of Science and Engineering, acatech; German National Academy of Sciences, Leopoldina; Union of the German Academies of Sciences and Humanities, Akademieunion (2018): Coupling the different energy sectors. Options for the next phase of the energy transition. Berlin: Königsdruck.

Atlan, Henry (1974): On a formal definition of organization. In: Journal of Theoretical Biology 45 (2), pp. 295–304.

Ausfelder, Florian et al. (2017): Sektorkopplung. Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems (Schriftenreihe Energiesysteme der Zukunft). Berlin: Königsdruck.

Bauknecht, Dierk et al. (2018): Visionen und Pfadentscheidungen der Energiewende. Freiburg: Öko-Institut e. V.

Beckman, Svante (1994): On systemic technology. In: Jane Summerton (ed.): Changing large technical systems. Boulder: Westview Press, pp. 311–331.

Bender, Gerd (2005): Technologieentwicklung als Institutionalisierungsprozess. In: Zeitschrift für Soziologie 34 (3), pp. 170–186.

Bolton, Ronan; Foxon, Timothy (2015): Infrastructure transformation as a sociotechnical process. Implications for the governance of energy distribution networks in the UK. In: Technological Forecasting and Social Change 90, Part B, pp. 538–550. DOI: 10.1016/j.techfore.2014.02.017.

Büscher, Christian (2018): Framing energy as a sociotechnical problem of control, change, and action. In: Christian Büscher, Jens Schippl and Patrick Sumpf (eds.): Energy as a sociotechnical problem. An interdisciplinary perspective on control, change, and action in energy transitions. London: Routledge, pp. 14–38.

Büscher, Christian; Schippl, Jens; Sumpf, Patrick (eds.) (2018): Energy as a sociotechnical problem. An interdisciplinary perspective on control, change, and action in energy transitions. London: Routledge.

Canzler, Weert; Knie, Andreas (2013): Schlaue Netze. Wie die Energie- und Verkehrswende gelingt. Munich: Oekom.

Cherp, Aleh; Vinichenko, Vadim; Jewell, Jessica; Brutschin, Elina; Sovacool, Benjamin (2018): Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. In: Energy Research & Social Science 37, pp. 175–190. DOI: 10.1016/j.erss.2017.09.015.

Covrig, Catalin; Ardelean, Mircea; Vasiljevska, Julja; Mengolini, Anna; Fulli, Gianluca; Amoiralis, Eleftherios (2014): Smart grid projects outlook 2014. Luxembourg: Publications Office of the European Union.

David, Martin; Gross, Matthias (2019): Futurizing politics and the sustainability of real-world experiments. What role for innovation and exnovation in the German energy transition? In: Sustainability Science 14 (4), pp. 991–1000.

Droste-Franke, Bert et al. (eds.) (2012): Balancing renewable electricity. Energy storage, demand side management, and network extension from an interdisciplinary perspective. Berlin: Springer.

Dürr, Thomas; Heyne, Jean-Christoph (2017): Virtuelle Kraftwerke für Smart Markets. In: Oliver Doleski (ed.): Herausforderung Utility 4.0. Wie sich die Energiewirtschaft im Zeitalter der Digitalisierung verändert. Wiesbaden: Springer Vieweg, pp. 653–681.

Edwards, Paul (2004): Infrastructure and modernity. Force, time, and social organization in the history of socio-technical systems. In: Thomas Misa, Philip Brey and Andrew Feenberg (eds.): Modernity and technology. Cambridge: MIT Press, pp. 185–225.

Fouquet, Roger (2016): Historical energy transitions. Speed, prices and system transformation. In: Energy Research & Social Science 22, pp. 7–12.

Gallagher, Kelly; Grübler, Arnulf; Kuhl, Laura; Nemet, Gregory; Wilson, Charlie (2012): The energy technology innovation system. In: Annual Review of Environment and Resources 37 (1), pp. 137–162. DOI: 10.1146/annurev-environ-060311-133915.

Geels, Frank (2004): From sectoral systems of innovation to socio-technical systems. Insights about dynamics and change from sociology and institutional theory. In: Research Policy 33 (6–7), pp. 897–920.

Geels, Frank (2014): The arduous transition to low-carbon energy. A multi-level analysis of renewable electricity niches and resilient regimes. In: Jan Fagerberg, Steffan Laestadius and Ben Martin (eds.): The triple challenge for Europe. Economic development, climate change, and governance. Oxford: Oxford University Press, pp. 91–118.

Grin, John; Rotmans, Jan; Schot, Johan (2010): Transitions to sustainable development. New directions in the study of long term transformative change. New York: Routledge.

Hagens, Nathan (2020): Economics for the future. Beyond the superorganism. In: Ecological Economics 169, p. 16. DOI: 10.1016/j.ecolecon.2019.106520.

Hoffrichter, Albert; Beckers, Thorsten (2018): Cross-border coordination as a prerequisite for efficient sector coupling in interconnected power systems. Institutional economic considerations on allocating decision-making competencies in the European Union. Berlin: Technische Universität Berlin.

Hughes, Thomas (1983): Networks of power. Electrification in Western society, 1880–1930. Baltimore: The Johns Hopkins University Press.

Kröger, Wolfgang; Nan, Cen (2018): Power systems in transition. Dealing with complexity. In: Christian Büscher, Jens Schippl and Patrick Sumpf (eds.): Energy as a sociotechnical problem. An interdisciplinary perspective on control, change, and action in energy transitions. London: Routledge, pp. 41–78.

Künneke, Rolf; Groenewegen, John; Ménard, Claude (2010): Aligning modes of organization with technology. Critical transactions in the reform of infrastructures. In: Journal of Economic Behavior & Organization 75 (3), pp. 494–505.

Milchram, Christine; Hillerbrand, Rafaela; van de Kaa, Geerten; Doorn, Neelke; Kunneke, Rolf (2018): Energy justice and smart grid systems. Evidence from the Netherlands and the United Kingdom. In: Applied Energy 229, pp. 1244–1259. DOI: 10.1016/j.apenergy.2018.08.053.

Nightingale, Paul; Brady, Tim; Davies, Andrew; Hall, Jeremy (2003): Capacity utilization revisited. Software, control and the growth of large technical systems. In: Industrial and Corporate Change 12 (3), pp. 477–517.

Robinius, Martin et al. (2017 a): Linking the power and transport sectors. Part 1: Modelling a sector coupling scenario for Germany. In: Energies 10 (7), p. 22. DOI: 10.3390/en10070956.

Robinius, Martin et al. (2017 b): Linking the power and transport sectors. Part 2: Modelling a sector coupling scenario for Germany. In: Energies 10 (7), p. 23. DOI: 10.3390/en10070957.

Roe, Emery; Schulman, Paul (2016): Reliability and risk. The challenge of managing interconnected infrastructures. Stanford: Stanford University Press.

Schuitmaker, Tjerk (2012): Identifying and unravelling persistent problems. In: Technological Forecasting and Social Change 79 (6), pp. 1021–1031.

van Lente, Harro (2000): Forceful futures. From promise to requirement. In: Nik Brown, Brian Rappert and Andrew Webster (eds.): Contested futures. A sociology of prospective techno-science. Aldershot: Ashgate, pp. 43–63.

Weick, Karl; Sutcliffe, Kathleen; Obstfeld, David (2005): Organizing and the process of sensemaking. In: Organization Science 16 (4), pp. 409–421.

DR. CHRISTIAN BÜSCHER
is since 2006 member of scientific staff at the Institute for Technology Assessment and Systems Analysis (ITAS). His research topics cover the theoretical embedment of technology assessment, social science-based energy research and risk and ecological sociology.

PRIV.-DOZ. MAG. DR. MICHAEL ORNETZEDER
is a Senior Researcher at the Institute of Technology Assessment (ITA), Austrian Academy of Sciences. He has PhD and post-doc level research and teaching experience in technology assessment and science and technology studies, with a particular focus on energy transitions, sustainable energy technologies, user innovation, and social learning.

DR. BERT DROSTE-FRANKE
is head of research at IQIB. His research interests are systems analyses, innovation analyses and technology assessment for policy advice, based on theoretical work, inter- and trans-disciplinary expert groups, quantitative analyses and modelling.